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The Role of Kinetic Effects and Wave-Wave Interactions in Stimulated Raman Backscattering in Long-Scale Plasmas

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Laser-plasma instability (LPI) research at Los Alamos is done as a closely coupled theoretical and experimental scientific program to advance the ignition and weapons physics enterprises, which are integrated by the US Department of Energy as a national program. Past LANL experiments, performed as part of the Nova Technical Contract, on hohlraum plasmas approaching NIF conditions have raised two main questions regarding stimulated Raman back-scattering (SRS) in such plasmas: 1) How can the high observed values of SRS reflectivity persist at $k\lambda_D = 0.3$ -- 0.45? 2) What are the non-linear mechanism(s) whereby SRS saturates? In this paper we address those two questions with results from experiments on the LANL Trident laser, and from Vlasov and PIC modeling of relevant plasmas, all aimed at understanding the physics involved. We find that non-Maxwellian distributions driven by intense ohmic heating, as well as electron trapping by the daughter SRS plasma wave, are implicated in the high SRS reflectivities observed at high values of $k\lambda_D$. We also find that electron trapping and the secondary Langmuir Decay Instability are important ingredients in the non-linear evolution of SRS.

1. Introduction

Laser scattering by stimulated laser-plasma instabilities (LPI) can severely limit the performance of targets for the next generation laser facilities, such as the National Ignition Facility (NIF), whether for inertial confinement fusion (ICF) or for other experiments. Backscattering can limit severely laser drive efficiency, potentially damage NIF optics and sometimes create hot electrons that preheat the target. Here we concentrate on the concerns for indirect-drive, where laser beams illuminate the interior of a cavity (called a hohlraum) to produce X-rays to drive the implosion of a fusion capsule or other targets. Ignition hohlraum designs planned for NIF use plasma pressure from a He-H gas fill to tamp the gold-wall plasma [1]. The underdense He-H plasma allows laser propagation within the hohlraum due to its low ionization state Z. High spatial-growth rates for stimulated Raman scattering [2] (SRS), *i.e.* scattering from electron plasma waves (EPW), and Brillouin scattering [3] (SBS), *i.e.* scattering from ion acoustic waves (IAW), are predicted in the long-scale (size ~ few mm) He-H plasma by linear convective theory [4], particularly for backscattering. With such high growth rates, these instabilities are expected to reach a non-linear state.

The quasi-homogeneous plasmas expected on NIF represent a qualitatively different regime compared to much of the existing LPI body of work, which begot the change towards UV lasers and underwrote the successful ICF programs at many laser facilities worldwide, such as Nova, Gekko, Omega, etc. Much of that LPI research used plasmas with relatively low electron temperature T_e so that $k\lambda_D \ll 1$, where k is the electrostatic wavenumber, $\lambda_D \propto (T_e / n_e)^{1/2}$ is the Debye length and n_e is the electron density. Such plasmas were typically small and the SRS spatial gain was limited by the density gradient $\nabla n_e \equiv n_e / L_n$ which causes a dephasing of the SRS resonance. In that case the spatial gain exponent scales as $G \propto I (\lambda_0)^2 L_n$, where I and λ_0 are the laser irradiance and wavelength, respectively. On the other hand, NIF plasmas are hotter ($k\lambda_D \sim 0.2 - 0.5$) and homogeneous over distances $L \gtrsim 1$ mm. In that case, the SRS gain exponent scales as $G \propto I\, L\, n_e / \nu_e$, where ν_e is the EPW damping rate. Thus, kinetic effects and the details of the plasma conditions can profoundly affect the SRS gain.

In order to study this new regime, many experiments were performed at Nova and other lasers as part of the *Nova Technical Contract* recommended in 1990 by the US National Academy of Sciences in a review of the US ICF program. LANL fielded experiments using gas-filled hohlraums that approached the plasma conditions expected within NIF ignition hohlraums at peak power [5]. In those experiments, SRS was seen to behave very non-linearly. As laser intensity was increased, the time-integrated SRS reflectivity rose sharply and then saturated at significant levels (~ 20%) [5]. As the damping rate of IAW was varied by changing the gas-fill mixtures, the reflectivity scaled linearly with the damping rate, even though IAW are not directly involved in SRS [6]. As $k\lambda_D$ was varied over the range of 0.3 – 0.45 by varying the electron density, the reflectivity remained at ~ 10% during the most quiescent time in the hydrodynamic evolution of the plasma [5]. This last observation is difficult to explain if one makes the usual assumptions that the electron velocity distribution is close to a Maxwellian, and that ν_e is given by linear (Landau) collisionless damping. In that case, ν_e is very high at $k\lambda_D \sim 0.4$ and there is not enough SRS gain to account for the observed SRS reflectivities. If in order to explain the high reflectivities at $k\lambda_D \sim 0.45$ we assume a non-thermal level of noise, or a non-Maxwellian distribution function due to intense ohmic heating [7] leading to a much lower ν_e , then the question remains of why the reflectivity stays constant as $k\lambda_D$ is decreased or the laser intensity is increased. Thus, two fundamental questions are raised by this work: 1) How can high SRS reflectivity persist at high $k\lambda_D$; and 2) How does SRS saturate? In trying to answer these questions experimentally, one has to contend with the complications in real experiments. These include SRS detuning caused by the hydrodynamic evolution of the plasma, the laser speckle in conventional laser beams and filamentation. The need to isolate SRS from any of these other issues has lead to a unique new experimental program on the Trident laser at Los Alamos.

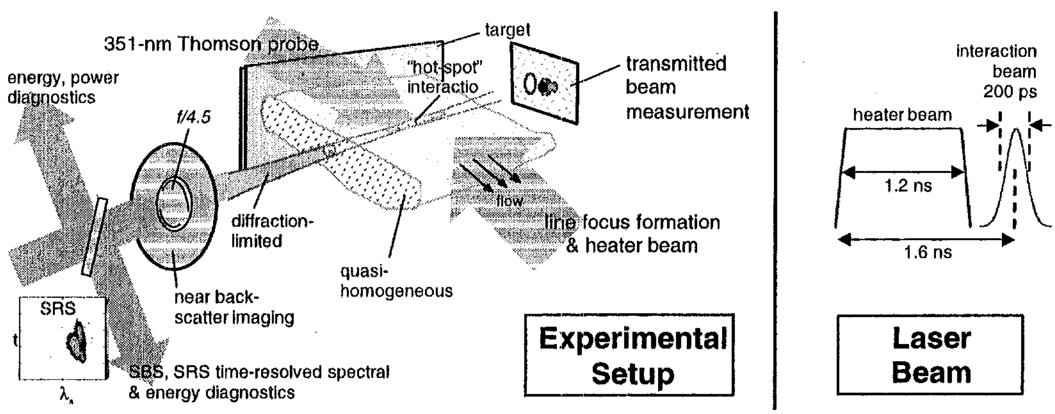

Fig. 1: Typical experimental configuration for the Trident "single hot spot" experiments.

2. The "single hot-spot" experimental configuration

Detailed SRS modeling of LPI processes in a NIF-scale plasma with thousands of speckles (hot spots) over time scales of interest will remain impossible until some suitable "reduced-scale" model is developed and coupled to a suitable radiation-hydrodynamics code. As a first step in order to elucidate the physics processes that are needed in such a model, we have embarked on the "single-hot spot" experimental program at Trident. The typical experimental setup is shown in Fig. 1. A nearly diffraction-limited beam, the "single hot spot" (SHS) beam, is used as a mathematically proper surrogate for a single speckle in a conventional beam. The wavelength of the SHS beam is 527 nm. It is placed in a preformed, well-characterized plasma from an exploding foil target that is homogeneous over the scale of the Raleigh length of the SHS beam. The measured transverse density scale length (~ 200 μm) is much larger than the width of the SHS beam (~ $f\lambda_0$ = 2.4 μm), and the longitudinal plasma dimension (~ 1000 μm) is much larger than the focal depth (~ $7f^2\lambda_0$ = 75 μm) [8]. The size of the interaction region is sufficiently small to allow complex simulations of the experiment, including particle-in-cell (PIC) [9] and Vlasov [10] modeling. In this configuration, a range of n_e can be chosen by proper placement of the SHS beam, and T_e can be varied somewhat by varying the power of the heater beam. Within the available parameters, a regime was identified where SRS and SBS backscattering, as well as filamentation were negligible, and only beam deflection by plasma flow was active [11]. Under those conditions, a 3D fluid model with non-local heat transport was sufficient to describe beam propagation. This gives us confidence that we understand beam propagation as we change conditions slightly to study SRS. At sufficiently low n_e and high transverse flow velocity we find regimes where filamentation is not dominant, SBS is negligible and significant SRS reflectivities are measured ($\lesssim$10%). For typical CH plasmas in these conditions, T_e ~ 350 eV and n_e / n_c ~ 3% as measured with Thomson scattering.

3. High reflectivity at high $k\lambda_D$:

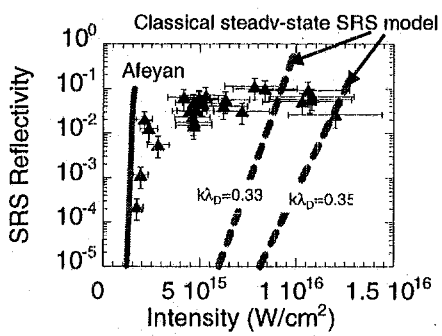

Fig. 2: Measured peak SRS reflectivity Vs SHS beam irradiance.

Fig. 2 shows the observed peak SRS reflectivity of the SHS beam. These data are reminiscent of the Nova data described above, which gives us hope that our increased understanding will be applicable to the larger NIF plasmas. Calculated reflectivity Vs irradiance curves, assuming linear SRS gain and Landau damping from a Maxwellian electron velocity distribution, are also shown for the range of $k\lambda_D$ fitting within the measurement uncertainties. A more sophisticated calculation using the 3D model described above for a laser intensity slightly above the observed threshold also yields a predicted SRS reflectivity much lower than observed, around 10^{-10}. These results indicate that ν_e is much lower than the classical value. If one assumes instead that the velocity distribution deviates from a Maxwellian as done in Ref. [7], we can match much better the observed SRS onset. However, the question of how does SRS saturate (just below 10% in this case) remains.

Another important culprit driving non linear SRS behavior is electron trapping by the plasma wave for those electrons near the wave phase velocity [12]. PIC simulations for a single speckle in NIF-like plasma conditions show very high reflectivities persisting at $k\lambda_D$ ~ 0.45 [13]. Other PIC simulations [9] for conditions closer to Trident also show low ν_e and high SRS reflectivity, with clear signatures of significant electron trapping. As shown in Ref. [12] for an electrostatic wave with electric field amplitude E, electrons near the wave phase velocity will oscillate longitudinally at a frequency $\omega_B \propto E^{1/2}$. When the Landau damping rate is lower than ω_B the approximations used by Landau become invalid and the collisionless damping rate becomes negligible compared to collisions and transverse particle loss from the hot spot due to finite electron temperature.

Trapping not only decreases ν_e, but also changes the character of the dispersion relation for electron waves. Fig. 3 (left) shows the dispersion relation for (undamped) electron waves when trapping is important, as calculated in 1D with the Vlasov and Poisson equations neglecting collisions and particle losses. In addition to the usual EPW branch, there is a lower frequency acoustic-like branch of electron waves. Moreover, there is a wave cutoff at $k\lambda_D$ ~ 0.5! The corresponding plasma conditions for our Trident experiments are indicated in the figure. This type of dispersion relation is supported by Trident observations so far. Fig. 3 (center) shows the observed stimulated backscattered light observed on these Trident experiments, plotted Vs phase velocity v_ϕ of the electrostatic wave (normalized to the electron thermal speed v_e) [10]. The backscattered light from normal SRS can be seen at v_ϕ /

$v_e \sim 4.1$. But at $v_\phi / v_e \sim 1.4$, there is another source of backscattering (scaled up by 1000 for visibility), just as predicted for the acoustic branch in Fig. 3 (left). This is the first observation of stimulated electron acoustic scattering (SEAS) in laser plasmas [10]. Although SEAS is energetically small in this case, it is an undeniable signature of the importance of trapping in these plasmas. The linear damping rate for the EAW wave is enormous and SEAS would not occur if linear theory applied. This is why the linear dielectric plasma response shown as the dotted line in Fig. 3 (right) shows a negligible response at the EAW phase velocity. On the other hand, a non-linear 1D Vlasov model that allows for trapping and includes an estimated effective wave damping from transverse particle loss shows a finite response at the EAW phase velocity. This model yields a dispersion relation (dependent on the wave amplitude) that looks very similar to that in Fig. 3 (left), except that the cutoff value of $k\lambda_D$ decreases slightly as the wave amplitude is increased.

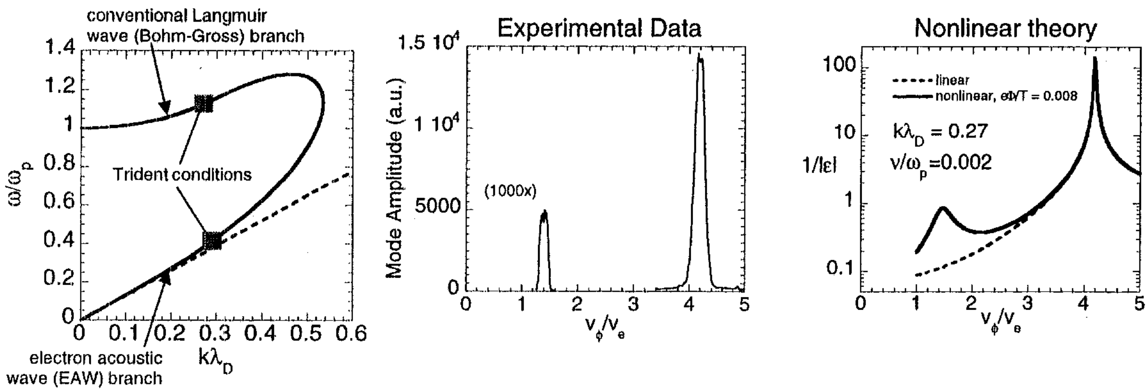

Fig.3 (left): collisionless Vlasov dispersion relation for electron waves; (center): observed backscattered light versus normalized phase velocity for the electrostatic wave; (right): dielectric plasma response versus normalized phase velocity calculated with Vlasov modeling including an effective damping rate to account for transverse electron loss.

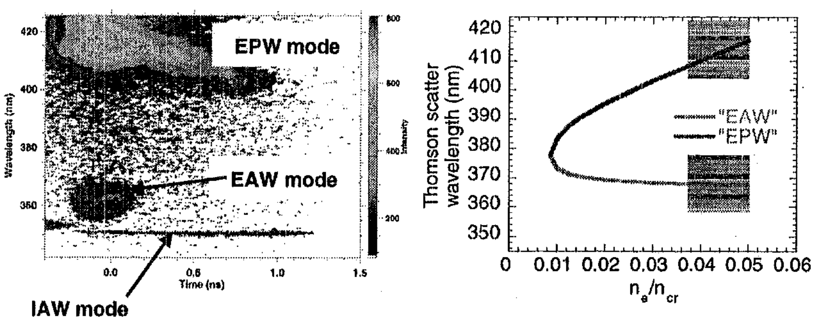

Fig. 4 (left): Thomson scattering signal from electron plasma waves responsible for backscattering an RPP beam on Trident plasmas; (right): possible Thomson scattering wavelengths from waves satisfying the collisionless Vlasov dispersion relation.

SEAS has now explained previous Thomson scattering observations [14] from similar Trident plasmas illuminated with a conventional laser beam smoothed by a random phase plate (RPP). This beam is much fatter than the SHS, comparable in size to the transverse density gradient. Therefore a range of densities (and thus $k\lambda_D$ values) are sampled by the beam. Based on the dispersion relation for electron waves in Fig. 3 (left), Fig. 4 (right) shows the locus of possible Thomson scattering wavelengths for this experiment. SEAS can explain the mysterious scattering signal at around 360 nm shown in Fig. 4 (left).

When the electrostatic wave amplitude is large enough, it is understandable that trapped electrons might result in very low damping rates for electron waves. But it is not clear how SEAS could get started from noise. Contrary to the SRS case, laser-modified distribution functions should have similar damping rates to a Maxwellian distribution at $v_\phi / v_e \sim 1.4$.

4. SRS saturation

It would seem that once particle trapping becomes significant, there would be no mechanism for SRS to saturate. However, wave-particle effects are also implicated in the saturation of SRS. As seen in the PIC simulations in Ref. [9], trapped particles interact non-linearly with the electrostatic wave, causing the resonance to detune. The result is that high SRS reflectivity comes in bursts of ~ 0.2 ps. The same PIC modeling, when applied to ions, yields much of the same particle trapping behavior for SBS as for SRS.

Wave-wave effects must be considered also for SRS saturation. Specifically, the SRS EPW could drive the Langmuir decay instability (LDI), where the EPW decays into a backward propagating EPW and a forward propagating IAW. In principle the first LDI EPW can itself undergo LDI, and so on, setting an LDI cascade. For sufficiently low damping of the LDI daughter waves, the resulting spectrum could become turbulent. To the extent that the daughter LDI waves are damped, LDI could be a factor in SRS saturation directly. But even if LDI does not saturate SRS directly, the ponderomotive force of the LDI EPWs could be large enough to modify the plasma conditions, thus affecting the evolution of SRS indirectly.

LDI cascading driven by SRS has been directly observed in these Trident plasmas in SHS experiments [15]. Because of the plasma homogeneity over the SHS dimension, this is the first unambiguous observation of distinct LDI cascades (as opposed to turbulence) in laser plasmas. It is not understood yet whether LDI is a dominant factor in SRS saturation, but its presence indicates that further consideration is required.

5. Summary

We have described our program for understanding the physics behind Raman backscattering in NIF-relevant plasmas. We are addressing the problem with results from experiments on the LANL Trident laser, and from Vlasov and PIC modeling of relevant plasmas, all aimed at understanding the physics mechanisms involved. We find that non-Maxwellian distributions driven by intense ohmic heating, as well as electron trapping by the daughter SRS plasma wave, are implicated in the high SRS reflectivities observed at high values of $k\lambda_D$. The discovery of stimulated electron acoustic scattering in our laser plasmas is another manifestation of the importance of particle trapping. We also find that electron trapping and the secondary Langmuir Decay Instability are important ingredients in the non-linear evolution of SRS. This work has been sponsored by the US Department of Energy.

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